

Frequency-tunable 500-mW continuous-wave all-solid-state single-frequency source in the blue spectral region

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A compact source of stable cw single-frequency radiation at 473 nm has been realized by second-harmonic generation of a diode-pumped miniature Nd:YAG ring laser operating on the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ laser transition. By use of potassium niobate (KNbO₃), single-longitudinal-mode output powers of 500 mW cw with high stability and maximum optical-to-optical conversion efficiencies >81% are achieved. An external semimonolithic cavity permits mode-hop-free frequency tuning of blue radiation over as much as 20 GHz. © 1997 Optical Society of America

Compact and efficient sources of stable, single-frequency radiation in the visible spectral region are attractive for numerous scientific and technical applications such as laser-based metrology, xerography, and biotechnology. Several of these applications benefit from shorter-wavelength light in the blue spectral region, which increases their spectral sensitivity or spatial resolution. However, current argon-ion (Ar⁺) or HeCd lasers suffer from extremely low efficiency, short lifetimes, and excessive optical-noise levels. Alternatively, as blue diode lasers such as InGaN compounds are in a very early stage of development,¹ efficient second-harmonic generation of diode lasers in appropriate nonlinear crystals such as potassium niobate (KNbO₃) was used for realization of compact devices with blue single-frequency output powers of as much as 156 mW.^{2,3} However, these devices have linewidths in the megahertz regime, and reliable single-mode operation is difficult to obtain.³

One can obtain substantially higher single-frequency output powers with excellent intensity and frequency stability by frequency doubling of diode-pumped solid-state lasers. Applying Nd:YAG as the active material, we recently reported stable 1.1-W cw single-frequency output power at 532 nm with high efficiency by use of a miniature ring laser operating on the ${}^4F_{3/2}$ - ${}^4I_{11/2}$ transition at 1064 nm.⁴ The generation of coherent blue radiation by frequency doubling of the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ quasi-three-level transition at 946 nm in Nd:YAG is possible.⁵ As much as 100-mW single-frequency output power at 473 nm in a twisted-mode cavity with a KNbO₃ crystal has been reported.⁶ However, output power, efficiency, and amplitude and frequency stability of such a laser system are limited by the necessary intracavity components.

In this Letter we report on a compact and efficient all-solid-state laser system that delivers 500-mW cw output power at 473 nm in a single longitudinal mode with high stability. For a diode-pumped laser system emitting in the blue spectral region this is to the best of our knowledge the highest value reported. Mode-hop-free frequency tuning of blue radiation is possible by use of an external semimonolithic cavity design.

The experimental configuration of the laser system is shown in Fig. 1. A quasi-monolithic ring laser crys-

tal,⁷ consisting of one 3-mm-long YAG crystal doped with 0.9-at. % Nd and one undoped YAG crystal optically bonded to each other, is mode-selectively pumped by four diode lasers (Opto Power Corporation, Tucson, Ariz.), each delivering 1.5 W at 808 nm. By applying an appropriate magnetic field along the crystal, we achieve stable single-frequency emission of 1.1 W cw at 946 nm with diffraction-limited beam quality and a 1-kHz linewidth. The output frequency is mode-hop-free tunable over a range of approximately 10 GHz by precise control of the laser crystal temperature, and fast-frequency tuning is possible by application of mechanical stress to the laser crystal with a piezoelectric transducer. We use a Faraday isolator (30-dB extinction) to avoid optical feedback from the external doubler cavity into the laser crystal. To obtain a dispersion-type error signal for locking the doubler cavity to the laser frequency, we apply a resonant phase modulator (New Focus, Model 4003-D). The total available power in front of the doubler resonator is 900 mW, of which >85% is matched to the fundamental transverse mode (TEM₀₀) of the cavity.

The semimonolithic doubler cavity consists of a 5-mm-long KNbO₃ crystal and an external 25-mm radius-of-curvature mirror separated by ~18 nm.

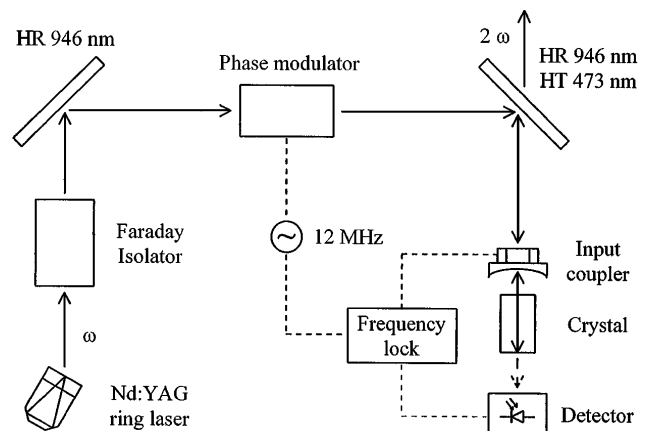


Fig. 1. Schematic of the experimental configuration (not to scale). The complete laser system covers a total area of 0.25 m² on an optical table. HR, high reflection; HT, high transmission.

Noncritical type I phase matching by means of temperature tuning would be possible with a nonlinear coefficient d_{eff} of approximately -20 pm/V, but the phase-matching temperature of 185°C is very close to a phase transition and requires very careful temperature changes for prevention of repoling of the crystal^{8,9}; hence, critical type I phase matching at 32°C is applied. For a fundamental beam of 946 nm that is propagating in the a - b plane of KNbO_3 crystal, angle-tuned phase matching with a $d_{\text{eff}} = -17.4$ pm/V and a walk-off angle $\rho < 0.86^\circ$ can be achieved.^{9,10} For the 5 -mm-long crystal, the angular, spectral, and temperature bandwidths are $\delta\theta = 2.5$ mrad, $\delta\lambda = 0.13$ nm, and $\delta T = 0.55^\circ\text{C}$, respectively.

The polished end faces of the KNbO_3 crystal are flat, the back face is dielectrically coated as a high reflector for 946 and 473 nm, and the front face is antireflection coated for both wavelengths. The crystal is wrapped in indium foil and mounted upon a thermoelectric cooler for active control of the crystal temperature. The external mirror, which we mounted upon a piezoelectric actuator to adjust the cavity length, transmits 3.7% at 946 nm and $>94\%$ at 473 nm and serves as an input coupler for the fundamental laser light and as an output coupler for the generated blue radiation. We chose the transmissivity of the fundamental wavelength for impedance matching of the input power with the total cavity losses to maximize the attainable conversion efficiency at the desired power level. The fundamental and the second-harmonic radiation are separated by a dichroic beam splitter that is dielectrically coated for high reflection for s -polarized 946 -nm radiation and high transmission ($T = 94\%$) for p -polarized 473 -nm radiation; both high reflection and high transmission are incident with an angle of 45° .

To keep the external doubler cavity resonant with the laser frequency in a simple and stable locking scheme, we used a modified Pound-Drever FM technique.¹¹ The fundamental beam is electro-optically modulated at 12 MHz by the resonant phase modulator, resulting in an amplitude modulation of the leakage wave through the high-reflection-coated end face of the KNbO_3 crystal. Mixing the ac components of the photodetector signal with the modulation source and the low-pass filtering results in a dispersion-type error signal, which is fed back to the PZT via a servo-loop amplifier for active control of the cavity length. The semimonolithic resonator design with an external mirror ensures a stable locking scheme without the need for feeding the error signal back to the laser, which would cause a deterioration in the laser's high intrinsic amplitude and frequency stability as well as cancel the possibility of tuning the frequency of the second-harmonic output by control of the laser frequency.

Because of the high nonlinear coefficient d_{eff} of KNbO_3 , efficient cw second-harmonic generation in an external cavity is possible without tight focusing. The chosen distance between the doubler crystal and the external mirror results in a beam waist of ~ 54 μm , located upon the back end face of the KNbO_3 crystal. Applying the theory of Boyd and Kleinman,¹² we obtain a focusing parameter $h(\sigma, \beta, \xi, \mu) = 0.091$, resulting in a maximum theoretical single-pass

nonlinear-conversion efficiency $\eta_{\text{NL}} = P_{2\omega}/P_{\omega}^2 = 1.72/\text{kW}$. In a linear enhancement cavity that is double passed by the harmonic wave as in the presented configuration, the nonlinear coupling can reach as much as four times this value, depending on the relative phase shift between the fundamental and the harmonic waves that is imposed by the dielectric coating.

In Fig. 2 the generated cw single-frequency output power at 473 nm is shown as a function of the fundamental power mode matched to the TEM_{00} eigenmode of the semimonolithic doubler cavity. The filled circles represent the measured second-harmonic power behind the dichroic beam splitter, and we obtain the open squares by correcting the data for the measured transmission losses of the beam splitter and a focusing lens (6% each). The squares are helpful for comparing the generated blue power with values expected from theory (solid curve)¹³ when the cavity losses L and the nonlinear coupling η_{NL} at low input-power levels are used as fitting parameters. For a fundamental power of 900 mW, of which $>85\%$ is mode matched, a maximum second-harmonic power in a single longitudinal mode of 500 mW cw is achieved, corresponding to an electrical-to-optical efficiency of nearly 2% . The optical-to-optical conversion efficiency when the measured second-harmonic power is used (filled circles) and the corrected values for the generated output power at 473 nm (open squares) are shown in Fig. 3. The solid curve is calculated from theory by use of the same parameters ($L = 0.4\%$, $\eta_{\text{NL}} = 1.78/\text{kW}$) as in Fig. 2. For mode-matched fundamental power levels as great as 340 mW there is good agreement with theory, resulting in a circulating fundamental power of nearly 14 W and a maximum optical-to-optical conversion efficiency of $>81\%$, which is to the best of our knowledge the highest value reported for KNbO_3 . For higher input-power levels the deviations between theory and experiment increase, probably because of power-dependent effects such as blue-light-induced IR

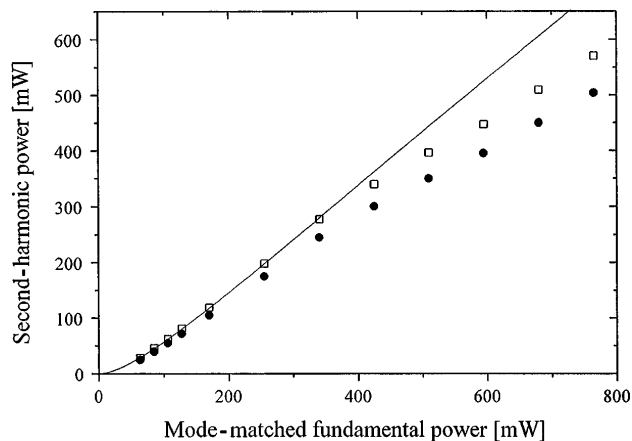


Fig. 2. Generated second-harmonic power as a function of the mode-matched fundamental power. The filled circles represent the measured single-frequency output power, and we obtain the open squares by correcting the data for the transmission losses at the dichroic beam splitter and a focusing lens. The solid curve is calculated from theory.

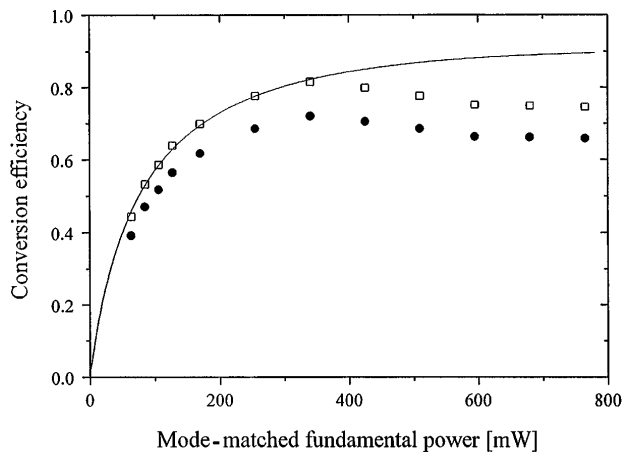


Fig. 3. Conversion efficiency as a function of the mode-matched fundamental power. The filled circles are calculated with the measured harmonic output power, and we obtain the open squares by correcting the data for the transmission losses as in Fig. 2 to characterize the crystal quality. The solid curve is calculated from theory.

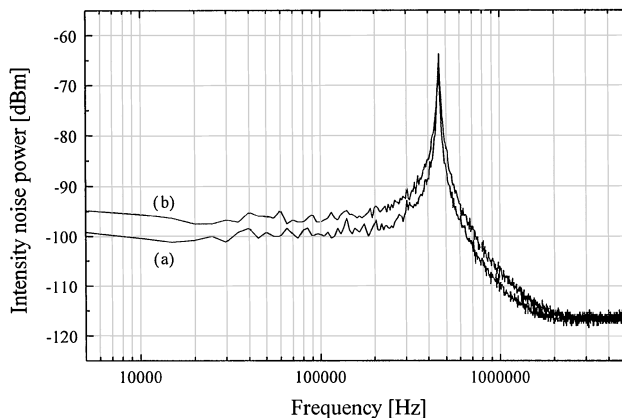


Fig. 4. Intensity-noise measurement for frequencies of as much as 5 MHz. Curve (a), fundamental light at 946 nm; curve (b) second-harmonic light at 473 nm. Both measurements were performed with the same photocurrent through the detector.

absorption¹⁴ as well as the development of thermal profiles inside the doubler crystal, causing phase-matching inhomogeneities. Similar effects were reported for a ring cavity used for frequency doubling of a watt-level cw titanium sapphire laser.¹⁵ Without these limiting factors the conversion efficiency would reach 90% for fundamental power levels of 900 mW.

To characterize the long-term intensity stability of the frequency-doubling setup, we recorded the generated second-harmonic output power for maximum fundamental input power for 1 h, resulting in a standard deviation for intensity fluctuations of 0.69%. We illustrate the intensity-noise spectra of the fundamental and the second-harmonic light, measured with the same photocurrent, in Fig. 4. As can be seen, no ad-

ditional noise features owing to mechanical resonances or electronic feedback are introduced. The dominating peak is caused by the resonant relaxation oscillations in the Nd:YAG laser crystal and can be substantially suppressed by use of a feedback circuit on the diode laser current.¹⁶

In conclusion, a diode-pumped single-frequency source in the blue spectral region that delivers 500 mW of cw power by frequency doubling a Nd:YAG miniature ring laser has been demonstrated. Using a semimonolithic KNbO₃ doubler cavity, we have achieved maximum optical-to-optical conversion efficiencies of >81%, with an overall electrical-to-optical efficiency of nearly 2%. Owing to the high intensity and frequency stability of the blue light and the possibility of mode-hop-free frequency tuning over as much as 20 GHz, this laser system is an interesting light source for various applications, e.g., laser-based metrology.

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